Modelling ensures a successful revamp

Pre-turnaround computational modelling built confidence in the benefits of introducing design changes to a FCC regenerator revamp

RAJ SINGH, PAUL MARCHANT and STEVE SHIMODA *TechnipFMC Process Technology*
MARC A SECRETAN *Suncor Energy*

For FCC operation, regenerator performance is a key factor in maximising unit economics. Regenerator performance is generally evaluated by uniformity of combustion, seen in the temperature profile, and strongly depends on good distribution of both air and spent catalyst. Both operating conditions and hardware configuration influence the air catalyst mixing and flow patterns within the regenerator.[1]

Understanding the impact of hardware configuration on regenerator fluidised bed hydrodynamics is important for any potential design modification, optimisation, and troubleshooting. It is important to pre-evaluate the performance of the unit with planned design modifications to reduce any unforeseen risks before the implementation. TechnipFMC actively uses computational fluid dynamics (CFD) tools for design validation and troubleshooting.

This article discusses an FCC regenerator revamp at the Suncor Edmonton refinery, aimed to incorporate advanced design features to mitigate operational challenges and improve the mechanical reliability of the internals. This article describes how CFD modelling tools were used to confirm the adequacy of the proposed hardware changes, fine-tune the design, and evaluate the performance to minimise risks on start-up. Post-turnaround performance of the unit confirms the benefit of the implemented design.

Suncor's Edmonton refinery is one of four refineries which Suncor operates in North America. The refinery was built in the 1950s, can process 142 000 b/d of crude, with FCC throughput of roughly 45 000 b/d. The FCC unit is a 'side by side' reactor/regenerator configuration which includes a close coupled riser termination device in the reactor and a regenerator with a fast burn zone. The layout of the FCC unit with its latest design features is shown in **Figure 1**. The unit has been revamped with multiple FCC Alliance (TechnipFMC, Axens, IFPEN, and Total) technology features in the last 20 years.

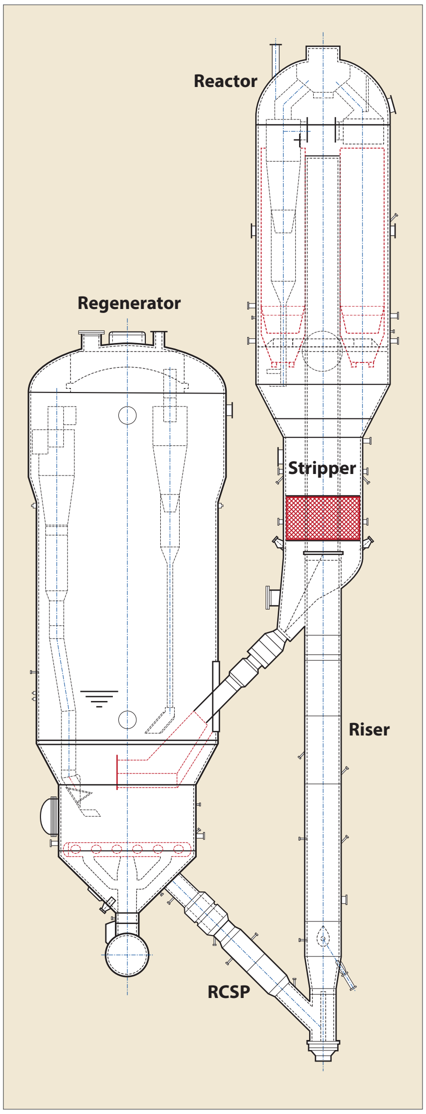

Figure 1 Suncor Edmonton refinery's FCC unit with key technology features

In 2001, FCC Alliance proprietary feed injectors and Suncor and TechnipFMC's jointly developed riser termination device were installed in the riser reactor section. Post-revamp, the unit performance was significantly enhanced due to improved feed atomisation and reduced post riser residence time. Even though the regenerator operation was switched from partial combustion to complete combustion, the unit managed to achieve higher catalyst to oil ratio and lower delta coke. The unit experienced improved yields; gasoline increased by approximately 5 vol% and coke decreased by 1 wt%.

In 2004, FCC Alliance's proprietary structured packing was installed in the FCC stripper. It was deemed a successful revamp as the unit was able to reduce the stripping steam consumption from 4lb to 2lb/1000lb catalyst circulation at a constant regenerator temperature. Since 2004, Suncor has inspected the packing during scheduled turnarounds and found no significant damage or erosion. It continues to perform effectively. Inspection pictures after 5, 10 and 14 years of service (see **Figure 2**) confirm that the packing is in good condition and continues to be reused.

Suncor's FCC regenerator is a single stage, full burn regenerator with a fast burn zone in the lower section of the regenerator. It operates at higher superficial velocities than typical regenerators. The original internals consisted of a single horizontal arm spent catalyst distributor, 'cross type' air grid distributor, and an internal hopper feeding the regenerated catalyst

Figure 2 Stripper packing inspection images

standpipe (RCSP). The regenerator was experiencing an afterburn of 40°F (22°C) which infringed on the turbo expander inlet temperature limit. Additionally, high gas entrainment into the RCSP led to poor head build-up and low regenerated catalyst slide valve (RCSV) pressure drop.

For the 2018 turnaround, as the regenerator was determined to be at end of life, Suncor decided to replace the entire vessel and internals such as the air grid, cyclones, spent catalyst distributor, and so on. The original objective was to be a replacement-in-kind revamp. However, Suncor took the opportunity to incorporate some design improvements to the regenerator internals to mitigate the known operational problems and improve the mechanical reliability of the internals. The regenerator shell design was kept unchanged to minimise impact on the foundation, structure, piping, and external work required during the turnaround. The existing top hemispherical head was replaced with an elliptical head to raise cyclone inlet elevation, while keeping the total regenerator height constant.

Technology and design development

During the planning stage, technology enhancements focused primarily on spent catalyst distribution and RCSP operation. A self-aerated, submerged compound angle spent catalyst distributor was designed to improve spent catalyst mixing in the bed, promote uniform bed combustion, and reduce afterburn. The RCSP inlet was modified to reduce gas entrainment, increase catalyst density, and improve head build-up above the RCSV. A comparison of the original regenerator configuration with the new/modified configuration, with changes highlighted in red, is shown in **Figure 3**.

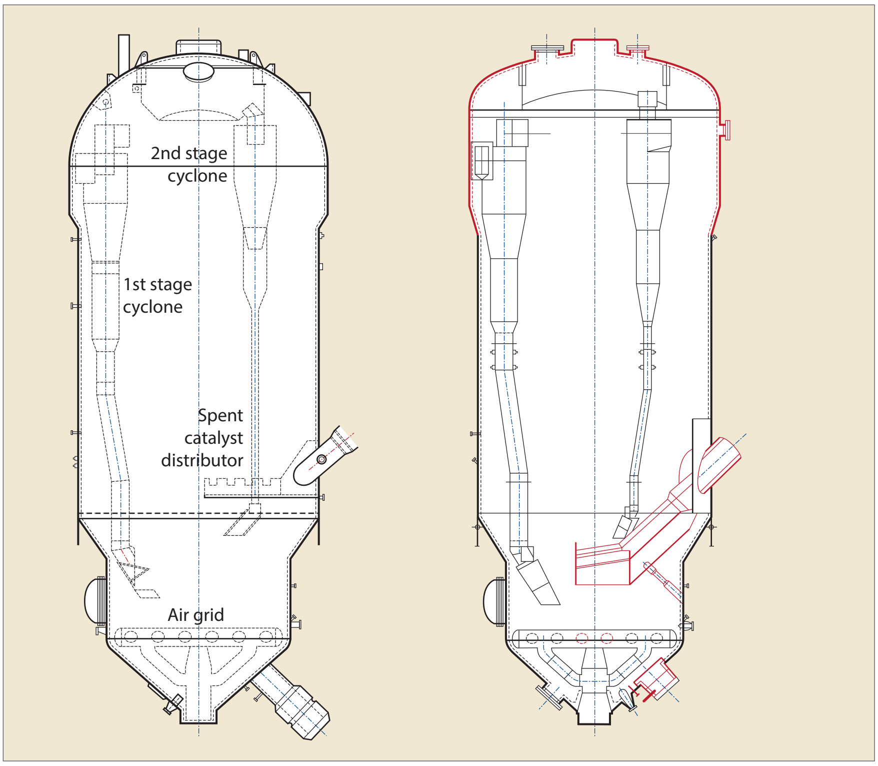

Figure 3 FCC regenerator: original (left) and modified (right)

The modified configuration in **Figure 3** shows an improved version of FCC Alliance's standard compound angle wye bathtub distributor design, where a major portion of the distributor arm is submerged in the catalyst bed. Considering the regenerator diameter was small and the standpipe inlet was tangential to the vessel, a one-arm bathtub instead of wye arms was designed for this application. The initial angle of the bathtub is optimised to ensure incoming spent catalyst has sufficient momentum to flow down the arm, without aeration, into the fluidised catalyst bed. The latter portion of the bathtub is designed to self-aerate, utilising the gas from the bed underneath, and distribute catalyst preferentially to the centre and sides of the vessel. The design provides self-fluidisation and eliminates the need for a sparger system to fluidise the catalyst in the distributor. The design allows the catalyst to discharge in the high velocity lower section of the regenerator, in close proximity to the primary cyclone dipleg discharge. This promotes spent catalyst interaction with hot catalyst returning from the primary diplegs and overall mixing in the bed, which is essential to enhance bed combustion uniformity and reduce afterburn.

Since the revamp was originally intended to replace the regenerator and its internals in kind, there was concern that the proposed hardware

changes may adversely impact the performance of the unit. To gain confidence in the likelihood of success and moreover to reduce any unforeseen risks, it was decided to evaluate and optimise the proposed design using computational fluid dynamics (CFD).

Computational modelling plays an increasingly important role in understanding gas particle flow dynamics in the FCC process, enabling designers to offer low risk, high value improvements. The latest generation of CFD modelling tools enables rapid exploration of different configurations to optimise the design. Compared to cold flow testing, CFD allows a deeper understanding of what is happening at all points in the system. It provides the qualitative information needed to visualise processes difficult to see in physical models, along with the quantitative results that enable realistic comparisons of equipment configurations. Combining these results provides an understanding of how hardware and operational changes impact gas catalyst flow dynamics in the fluidised bed. Conducting CFD 'virtual testing' of new devices, combined with experience, increases confidence in proposed changes.

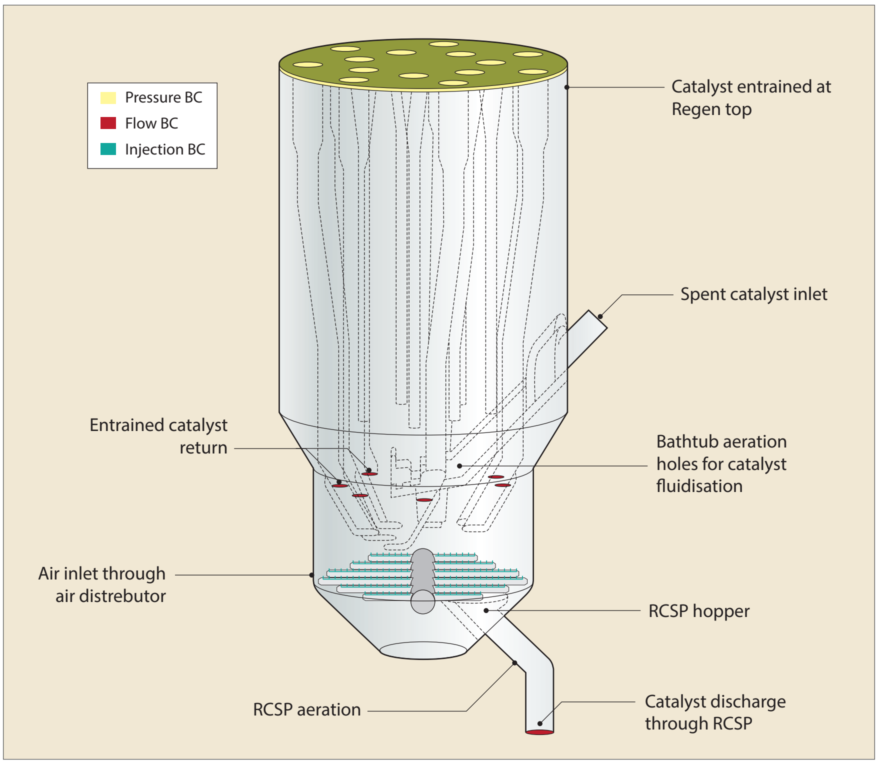

Figure 4 Regenerator modelling domain

Computational modelling

A CFD model was developed for the regenerator configuration with proposed internal modifications to study the impact on the fluidised bed hydrodynamics. Barracuda VR, CFD software developed exclusively to model gas solids fluidised bed reactors, was used for the study. The software was selected because of its capability to accurately handle dense gas solid flows. The algorithms and models incorporated into the Barracuda VR software have been validated against cold flow experimental data and commercial operating reactors.[2,3]

A portion of the regenerator section (see **Figure 4**) was selected as the modelling domain for the hydrodynamic study. It incorporates all the essential features of the regenerator which can influence the prediction of the regenerator bed's hydrodynamic behaviour, such as: primary and secondary diplegs returning entrained catalyst back to the bed to maintain bed level and temperatures; actual nozzle count and gas momentum through the air grid distributor; details of the new spent catalyst distributor, and others. The inlet and outlet flows are defined by pressure, flow, and injection boundary conditions. There were essentially two modelling cases: one with the regenerator configuration with the proposed spent catalyst distributor design and original RCSP hopper, and a follow-up case with no RCSP internal hopper.

Self-aerated submerged spent catalyst distributor

The modelling results from the base case regenerator configuration with the new spent catalyst distributor is shown in **Figure 5**. The gas catalyst flow pattern and mixing are represented by both instantaneous and time average catalyst volume fraction profiles at the centre line of the X and Y planes of the model, along with the radial contours of the catalyst density profile at selected elevations. Both the radial and axial plots indicate that the fluid and catalyst are well mixed in the bed, resulting in uniform catalyst density. No gas by-passing is observed in the results. The instantaneous plot of catalyst density signifies that the bed is highly active above the air distributor. This is primarily due to high superficial velocity in the regenerator lower section. Terminating the primary diplegs in the regenerator lower section tends to bring all the entrained hot catalyst back to the lower section of the regenerator and helps to maintain the bed densities as well as desired temperatures for combustion.

The performance of the new spent catalyst distributor was evaluated both qualitatively and quantitatively. A qualitative representation of the modelling results in terms of overall catalyst mixing, spent catalyst coverage, and catalyst species across the bed is shown in **Figure 6**. The presence of spent catalyst all over the regenerator clearly indicates that spent catalyst is completely distributed across the bed.

The quantitative results shown in **Table 1** confirm even distribution of spent catalyst from the distributor sides as per the proposed design. The CFD results also indicated that the flow from the distributor slots towards the wall is in very close proximity to one of the primary cyclone diplegs, which may cause erosion of the dipleg and

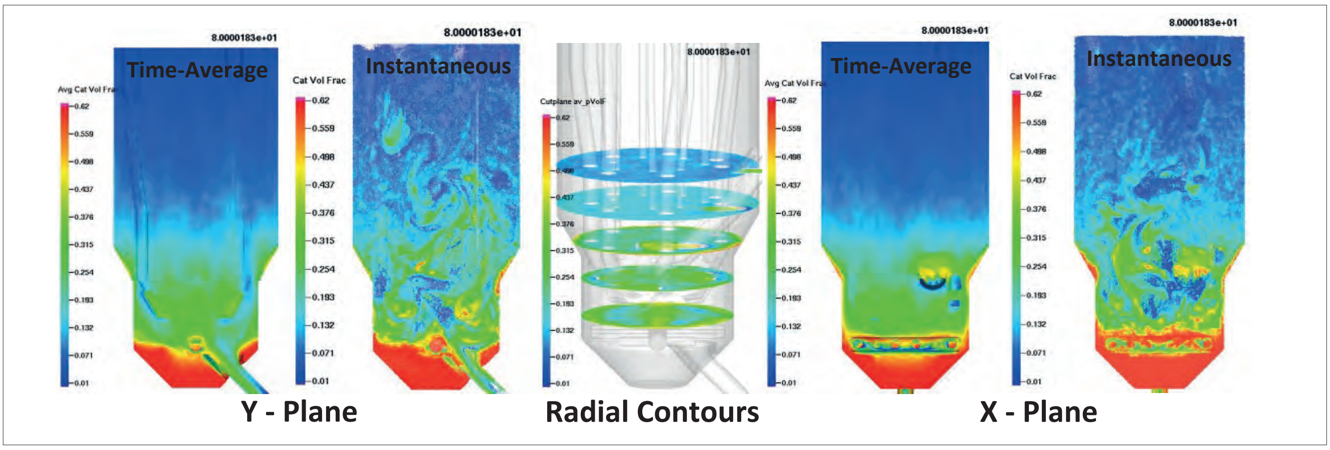

Figure 5 CFD prediction: catalyst density profile

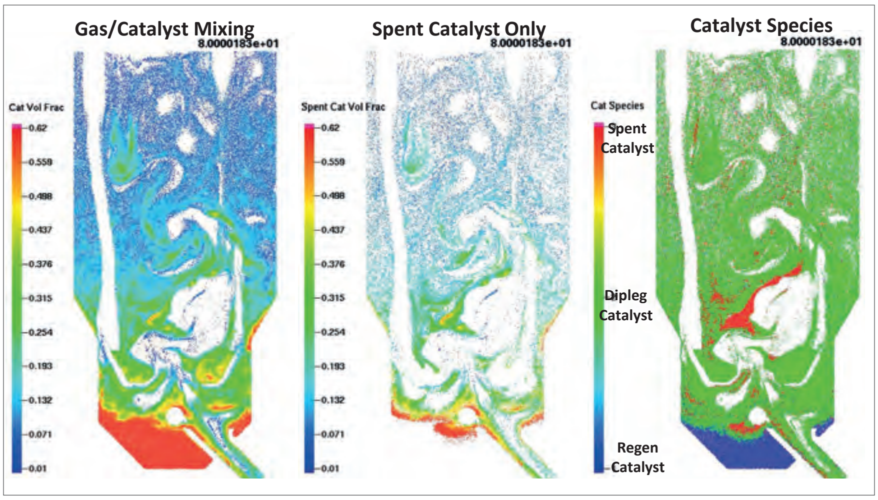

Figure 6 Regenerator centre line cut-plain: catalyst density and species plot

	Proposed design, %	Optimised design, %
Towards centre	43	62
Towards wall	43	23
From distributor end	14	12

Spent catalyst distribution

Table 1

disrupt valve opening and closing. Thus, the distributor slots towards the wall region were removed to increase catalyst flow towards the regenerator centre and reduce the potential for catalyst impingement on the cyclone dipleg valve concerned. Biased flow towards the centre further promotes spent catalyst coverage across the regenerator.

RCSP internal hopper

The original regenerator configuration had an eccentric internal catalyst hopper connected to the RCSP inlet nozzle (see **Figure 3**). The hopper was located a minimum distance below the air distributor and tended to withdraw catalyst directly from the active zone above the air grid distributor. The catalyst flux at the hopper inlet was approximately 60 lb/ft²/s which increases to 225 lb/ft²/s at the RCSP inlet in less than three seconds' residence time. The fact that the distributor was too close to the hopper, and the hopper was quite small, resulted in a lack of sufficient residence time for gas to disengage from downflowing catalyst into the RCSP. This resulted in high gas entrainment, which further caused low catalyst density and low head build-up in the standpipe. This analysis was supported by both plant data as well as findings from CFD modelling results.

The regenerator operating data versus pressure drop along the RCSP is plotted in **Figure 7** as a function of regenerator superficial velocity at constant catalyst circulation. The plot shows a decrease in head gain with an increase in superficial velocity, which is generally due to increased gas entrainment down the standpipe.

CFD predictions of regenerator configuration with and without an internal RCSP hopper are compared in **Figure 8**. Both the configurations are modelled with the new spent cat-

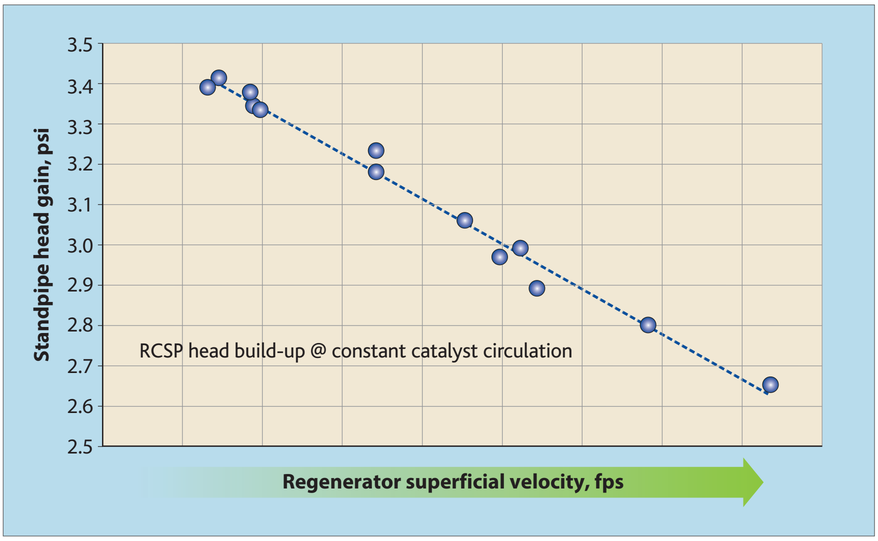

Figure 7 RCSP pressure build-up vs regenerator superficial velocity with internal hopper

alyst distributor, and the RCSP hopper is removed to evaluate its impact on spent catalyst flow and gas entrainment into the RCSP. **Figure 8** shows the time average axial distribution of catalyst volume fraction along the regenerator centre line and represents catalyst density distribution in the bed as well as in the RCSP inlet. The bed is uniformly mixed with and without the RCSP hopper and there is no significant change in gas catalyst flow pattern above the air distributor. The hopper mainly withdraws catalyst from the active zone above the air grid and draws an excess amount of gas into the RCSP. The results clearly show high gas entrainment and low catalyst density with the RCSP hopper.

With no RCSP hopper, CFD predicts the catalyst flow to the RCSP will be 40% denser, which indicates directionally less gas entrainment and improved RCSP head build-up. Additionally, Barracuda VR has a useful feature in that catalyst 'in the bed' and incoming spent catalyst can be tracked separately. The RCSP hopper draws catalyst from above the air grid and increases the chances of 'bypassing' spent catalyst into the RCSP, estimated at about 11% of spent catalyst short-circuiting into the RCSP with a residence time of less than 60 seconds in the system. Removing the hopper and drawing catalyst preferentially from below the air grid reduces the amount of bypass to around 5%. Based on the CFD findings, the following modifications were made to the RCSP inlet:

- Removed the RCSP hopper and increased the RCSP inlet nozzle size to reduce catalyst flux at nozzle inlet
  - Increased residence time for gas to disengage from downflowing catalyst into the RCSP
  - Reduced gas entrainment, increased catalyst density, and improved standpipe pressure head
- Provided fluidisation nozzles close to the RCSP inlet to keep the RCSP inlet region fluidised to aid smooth transfer of catalyst from regenerator to RCSP
- Provided debris guard

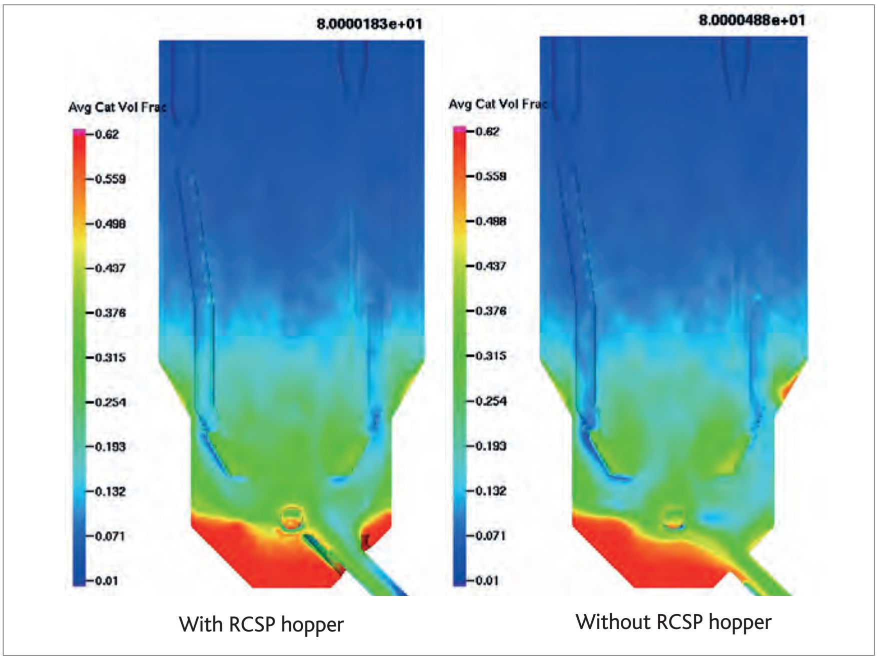

Figure 8 Density plot comparison: with and without RCSP hopper

Figure 9 Installation of spent catalyst distributor

Unit operation

After fabrication of the regenerator vessel along with its internals, the vessel was placed on a temporary structure on-site before it was swapped with the original vessel during the turnaround. The installation of the spent catalyst distributor in the regenerator vessel is shown in **Figure 9**. The unit has been in operation for more than two years since turnaround, showing significant improvement in unit performance.

The performance of the regenerator before and after the turnaround is shown in **Figures 10** and **11**. More than a 50% reduction in dense and dilute phase temperature variation (see **Figure 10**) after turnaround clearly represents the benefit of the newly implemented spent catalyst distributor in achieving uniform combustion and temperature profile within the catalyst bed.

Figure 11 shows the afterburn data with respect to both dilute phase and overhead flue gas temperature. The afterburn, with respect to dilute phase temperatures, dropped by roughly 15°F (8°C) whereas the overhead flue gas temperature showed a 35°F (19.5°C) drop in temperature, resulting in minimal afterburn with the submerged compound angle bathtub distributor.

The pre- and post-turnaround operating conditions and yields, compared in **Table 2**, clearly indicate the benefit of incorporating advanced regenerator internals into the operation. High levels of

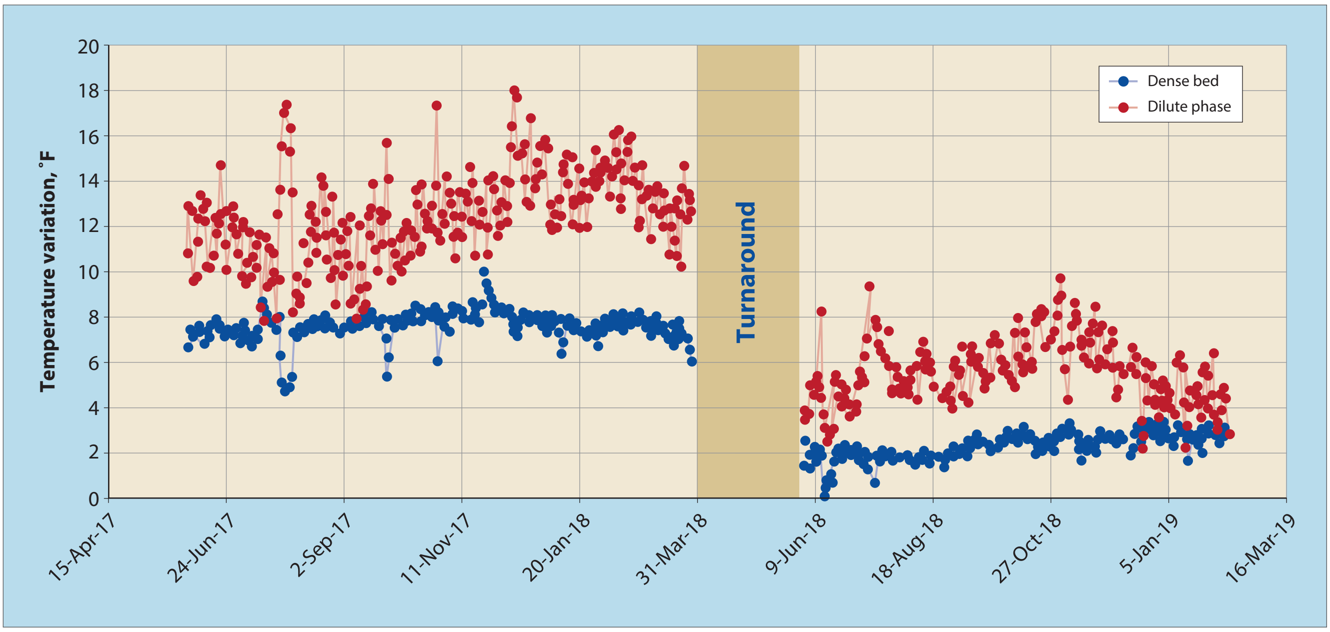

Figure 10 Pre/post-operating data: dense and dilute phase temperature variation

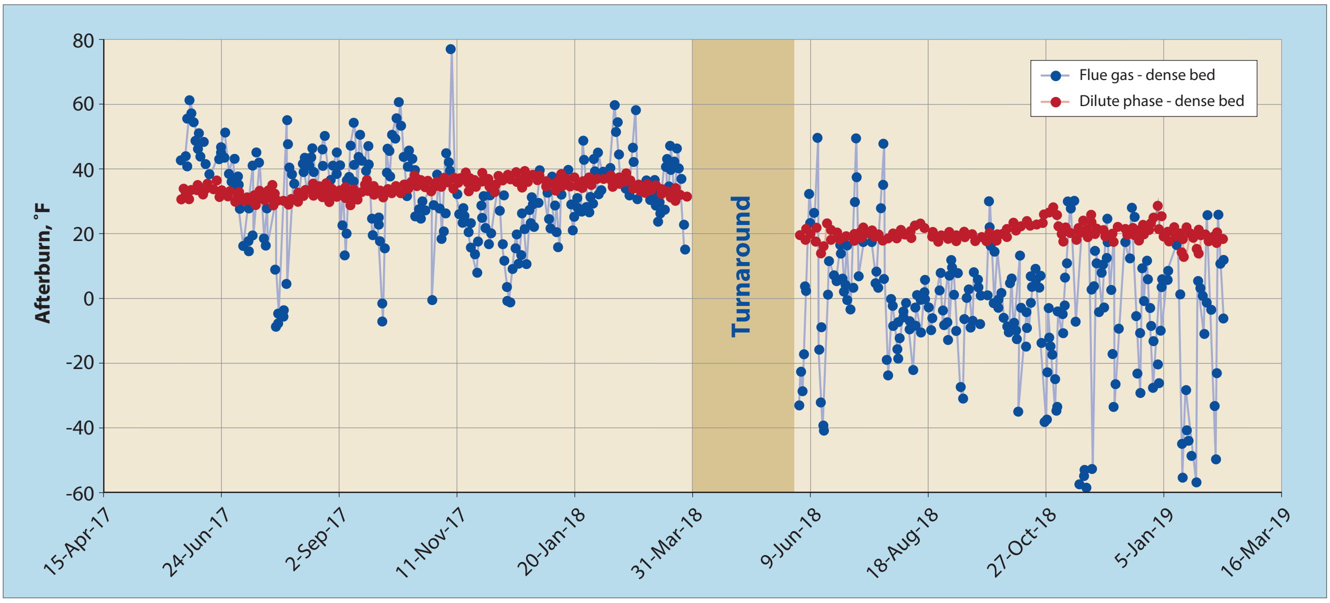

Figure 11 Pre/post-operating data: afterburn

throughput, catalyst circulation, and conversion have been achieved without encountering flue gas temperature limits. Modifications to the RCSP inlet proved to be beneficial in reducing gas entrainment into the RCSP and increasing standpipe head gain by 1.3 psi.

Conclusion

Implementing any new technology or design brings with it attendant risks as the real-world performance is not known. Success depends on properly planning all phases of the project including conception, process design, mechanical design, fabrication, installation and finally start-up. All stakeholders must understand the design intent and have a high degree of trust in each other. For the Suncor revamp, the original intent was to replace in kind. However new design concepts were considered and implemented to realise improved process performance and mechanical reliability.

To increase confidence in the design, TechnipFMC prepared a CFD model of the design to demonstrate that improved process performance would be achieved. The purpose of modelling was to indicate improved spent catalyst distribution as well as improved standpipe pressure build-up. Accurate system modelling allowed proper design evaluation. The CFD tools helped all stakeholders to develop confidence in the proposed changes.

Collaboration between process and mechanical designers continued throughout detailed engineering, fabrication, and installation phases. Following the turnaround, unit start-up was trouble free, and once the unit stabilised the process data indicated that the distributor was working as intended. Variation in the dense bed temperature and reduced afterburn were a clear indication of improved distribution. Catalyst circulation was smooth and RCSP pressure build-up was

improved, indicating better performance at the inlet.

Barracuda VR is a registered trademark of CPFD Software.

Unit operation comparison			
	Pre T/A	Post T/A	Delta
Key operating conditions			
Throughput, b/d	Base	+	2.60%
ROT, °F	975	968	-7
C/O	6.7	7.3	9%
Catalyst circulation, t/m	31.3	35.3	12%
Regen dense bed temp, °F	1260	1246	-14
Regen dilute phase temp, °F	1283	1261	-22
Regen flue gas, °F	1278	1246	-32
Yields, wt% FF			
Dry gas	1.8	1.7	-5.6%
LPG	18.7	18.5	-1.1%
Gasoline	56.5	57.1	1.1%
LCO	14.2	14.2	0.0%
Slurry	4.7	4.3	-8.5%
Coke	4	4.2	5.0%
Conversion, wt%	81.1	81.5	0.5%

Table 2

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Raj Singh is Senior Technologist, FCC Refining with TechnipFMC. With over 15 years of experience in FCC equipment design, technology development and troubleshooting, he has contributed to a wide range of projects, including revamps, grassroots designs, process studies, CFD studies, and FCC proposals. He holds a MS in chemical engineering from Illinois Institute of Technology, Chicago.
Email: raj.singh@technipfmc.com

Paul Marchant is the Process Manager, Refining with TechnipFMC in Houston Texas. He has worked on all aspects of FCC technology programmes and projects for over 20 years. He has been awarded several patents, and holds a BEng from the University of Bradford, UK.
Email: paul.marchant@technipfmc.com

Steve Shimoda is Director of the FCC programme with TechnipFMC. He has over 20 years of process technology experience with refining units. His current responsibilities include project development, technical marketing, and technology licensing. He holds a PhD in chemical engineering from the University of Houston and a BS in chemical engineering from the University of Oklahoma.
Email: steve.shimoda@technipfmc.com

Marc Secretan is FCC Engineering Specialist with Suncor in Calgary, Alberta. With over 20 years of experience in refining, his work has primarily focused on process improvement and optimisation, troubleshooting operational problems, unit start-ups, turnaround inspections, incident investigations, component design, risk assessment, and automation of FCC units. He holds a BSc degree in chemical engineering from the University of Alberta.
Email: msecretan@suncor.com